"InAsP/InGaAs Materials Development for 2.1 μm Avalanche Photodiodes"

Phase II SBIR contract #N00014-93-C-0254

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QUARTERLY REPORT #4
(6/94 - 8/94)

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Summary

A full 2.1 μm InAsP/InGaAs avalanche photodiode structure was fabricated, processed, and fully tested during the past quarter. Although results were disappointing, it was only a first try and in fact, represented a "leap" beyond our proposed schedule. Figures 1 through 3 contain summaries of the measured data. Briefly, breakdown voltages were below 10 volts and dark currents at -5V were in the microamp range. A cutoff wavelength of 2.10 μm was also measured. Avalanche gain was not observed under any conditions. We attribute to high dark currents to lattice mismatch at the InAsP/InGaAs interface and also the high background doping.

A paper, based on our Phase I results, has been written (copy attached) and is undergoing internal review before being submitted to IEEE Photonics Technology Letters.

Next Quarter Plans

We will once again "walk before we run" by repeating our Phase I experiments with a new twist: direct deposits of $InAs_yP_{1-y}$ upon p^+: InP substrates yielded low dark current, high breakdown voltage and avalanche gains of 10 - 40 (only for light of wavelength near 1 μm). A set of these epitaxial wafers will be grown in August and evaluated as in Phase I. Then, after avalanche gain is demonstrated, we will grow the lattice-matched $In_{.7}Ga_{.3}As$ absorbing layer (for λ = 2.1 μm light) and check to see if gain is still observed.

Phase II Statement of Work

The overall technical objective of this program is to advance the state-of-the-art of InAsP/InGaAs materials development so that 2.1 µm APDs which presently do not exist and offer *ten times* the light detection sensitivity of anything now available can be made.

Specific technical objectives include:

- Development of the hydride vapor phase epitaxial (VPE) compositional grading technique to achieve a lattice mismatch ($\Delta a/a$) between the adjacent $InAs_yP_{1-y}$ and $In_xGa_{1-x}As$ epitaxial layers of about 0.13% or less.

- Development of innovative annealing techniques to reduce or eliminate lattice mismatch dislocations and thereby reduce the leakage currents of 2.1 µm Avalanche Photodiodes (APDs).

- Fabrication and testing of mesa type APDs for reliability. This will include development of polyimide passivation techniques as well as silicon nitride and silicon oxynitride using Plasma Enhanced Chemical Vapor Deposition (PECVD).

- Calibration of avalanche gain (M) vs. reverse bias (V) at temperatures of 250, 260, 270, 280, 290, and 300K.

- Deliver five APDs having the following characteristics:

Active diameter	**100 µm**
Room temperature spectral response	**1.5 - 2.2 µm**
Responsivity at unity gain condition	**1.1 A/W @ 2.1 µm**
Avalanche gain @ 0.98 of V_B	**1 0**
Shot noise current	**<0.2 nA (rms) in a bandwidth of 100 MHz**
Rise time/fall time	**< 5 nsec**
Mean time to failure (MTTF)	**1 x 10^9 hours at 300K**

Phase II Work Schedule

Task		Personnel	Months
1.	**Preliminary Design Work**	GO, MC	0 - 3
-	Overall mask design for 50,100, 200, and 500 μm diameter devices		
2.	**Materials**	GO, RM	1 - 9
-	Calibrate VPE reactor		
-	Etch pit studies for dislocations in InP substrates		
-	Optimize graded layers of VPE In(As,P)		
3.	**Study Avalanche Breakdown in $InAs_{.4}P_{.6}$**	RM, SF, GO	3 - 9
-	Grow VPE InAsP on InP with variable EPD		
-	Fabricate mesa APDs of various diameter		
-	Measure Id, Vg, M vs. diameter and EPD		
4.	**Fabricate APDs in InAsP**	E1, T1, RM	9 - 12
-	Optimize thickness/doping profile		
-	Determine optimum geometries		
5.	**Fabricate InGaAs/InAsP "SAM" APDs**	GO, RM, T1	12 - 20
-	Confirm thickness/doping profiles		
6.	**Device Characterization (SAM-APDs)**	GO, RM, T1	14 - 24
-	Measure I_d, V_g, C and M vs diameter		
-	Profile gain across diodes		
-	Measure pulse rise/fall time vs diameter		
-	Perform noise measurements		
-	Measure gain/bandwidth product		
7.	**Temperature Behavior**	Mc, E2	17 - 20
-	Dark current and gain from 250 to 300K		
-	Spectral cutoffs from 250 to 300K		
-	Noise properties from 250 to 300K		
8.	**Reliability Studies**	MC, GO, RM	19 - 24
-	Hermetically seal 100 μm devices		
-	Bias for 98% of voltage breakdown at 200°C		
-	Measure 20°C I_d, V_g, and M every 1000 hours		
9.	**Deliverables**	GO, RM, SF	24
-	Quarterly Reports		
-	5 APDs		
-	Final Report		
10.	**Phase III Effort**		24 -

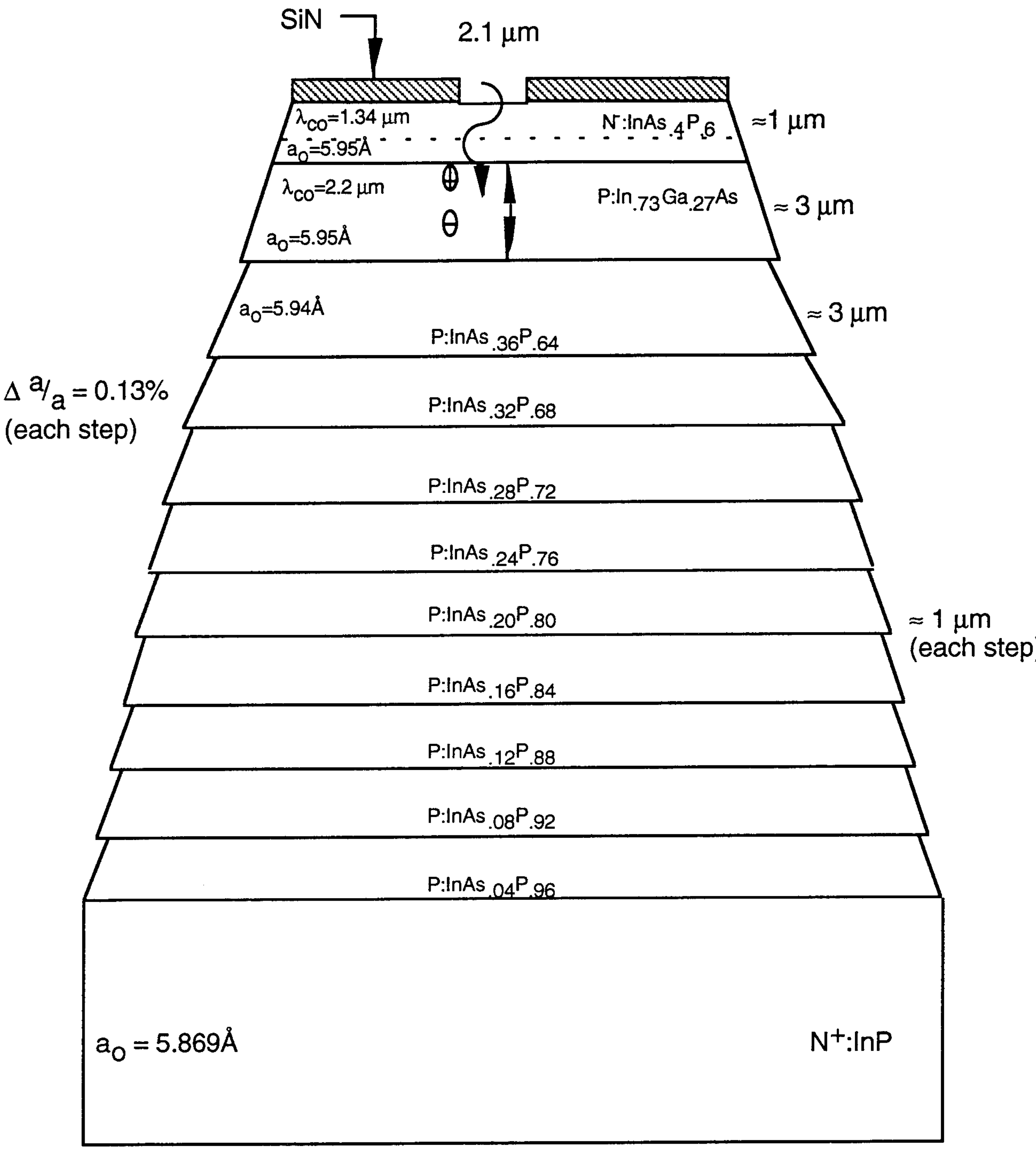


Figure 1. APD mesa structure which would absorb light out to 2.2 µm. Light absorption takes place in the $In_{.73}Ga_{.27}As$ while avalanche multiplication takes place in the uppermost $InAs_{.4}P_{.6}$ layer.

Results

The full 2.1 μm APD structure, as depicted in Figure 1 was grown and evaluated for lattice-mismatch and cutoff wavelength. Materials properties are listed in Table 1. Although parts of the wafer seem close to lattice-match, much of the wafer was not. While a smooth cross-hatch pattern usually associated with wafers that produce good devices was seen on most of the wafer, large pits were also observed which might indicate some anomaly during growth. The wafer was initially processed and evaluated before metal contacts were deposited. Results are shown in Figures 2 and 3 and in Table 2. High dark current (> 1 μA at 5V) and low breakdown voltage (< 10V) are evident. These measurements were repeated after metallization but improvement was not observed. Figure 4 contains a photograph of a finished metallized diode along with a current-voltage oscilloscope trace. The low (~3V) breakdown voltage and high (>1μA) dark currents explain why avalanche gain could not be achieved with light illumination. Figures 5 and Table 3 contain additional current - voltage data take from the fully metallized wafer. Several hundred diodes were fabricated and probe results from dozens of devices were recorded. We believe this data is typical of the entire wafer.

The remaining half of the wafer was processed again but results were equal or worse then those observed on the first process run. We concluded that low breakdown voltages and high dark currents were caused by flaws in the materials rather then processing difficulties.

One bright spot may be seen in Figure 6. The desired cutoff wavelength of 2.1 μm was in fact achieved with this wafer. Response at 2.06 μm was 80% of the full peak response measured from 1.6 to 2.0 μm. The abnormally low quantum efficiency (~1/2%) is due to the low breakdown voltage which would not allow enough reverse bias depletion to be achieved to sweep carriers out of the InGaAs and across the p/n junction located in the high bandgap InAsP. Achieving the desired cutoff wavelength was an important accomplishment for the program and demonstrated that our proposed Phase II structure can meet the spectral qualities that are required to make a high-quality 2.1 μm avalanche photodiode.

Table 1: InGaAs EPI Wafer Certificate

Structure	Carrier (cm^{-3})	Thickness (μm)			λc (μm)			Dopant
		up	down	avg.	up	down	avg.	
InAsxP (x=.40)	5.0×10^{17}	1.06	0.82	0.94				S
InxGa1-xAs (x-.73)	$< 3.0 \times 10^{15}$	3.00	2.82	2.91	2.03	2.10	2.07	non
InAsxP (x=.40)	$< 3.0 \times 10^{15}$	1.82	1.60	1.71				non
InAsxP (x=.40)	1.5×10^{17}	0.60	0.50	0.55				Zn
InAsxP (x=.36)	1.5×10^{17}	0.60	0.50	0.55				Zn
InAsxP (x=.32)	1.5×10^{17}	0.60	0.45	0.53				Zn
InAsxP (x=.28)	1.5×10^{17}	0.60	0.45	0.53				Zn
InAsxP (x=.24)	1.5×10^{17}	0.60	0.45	0.53				Zn
InAsxP (x=.20)	1.5×10^{17}	0.60	0.40	0.50				Zn
InAsxP (x=.16)	1.5×10^{17}	0.60	0.40	0.50				Zn
InAsxP (x=.12)	1.5×10^{17}	0.60	0.40	0.50				Zn
InAsxP (x=.12)	1.5×10^{17}	0.60	0.40	0.50				Zn
InAsxP (x=.08)	1.5×10^{17}	0.60	0.35	0.48				Zn
InAsxP (x=.04)	1.5×10^{17}	0.60	0.35	0.48				Zn
InP	1.5×10^{17}	0.60	0.50	0.55				Zn

Substrate	Orientation	(100) 2° off toward <110> ± 0.05°		
	EPD	5.0×10^{3} cm^{-2}	Dopant	Zn
	Diameter	50.0 ± 0.3 mm	Carrier	5.64×10^{13} cm^{-3}
	Thickness	350.0 ± 10.0 μm		

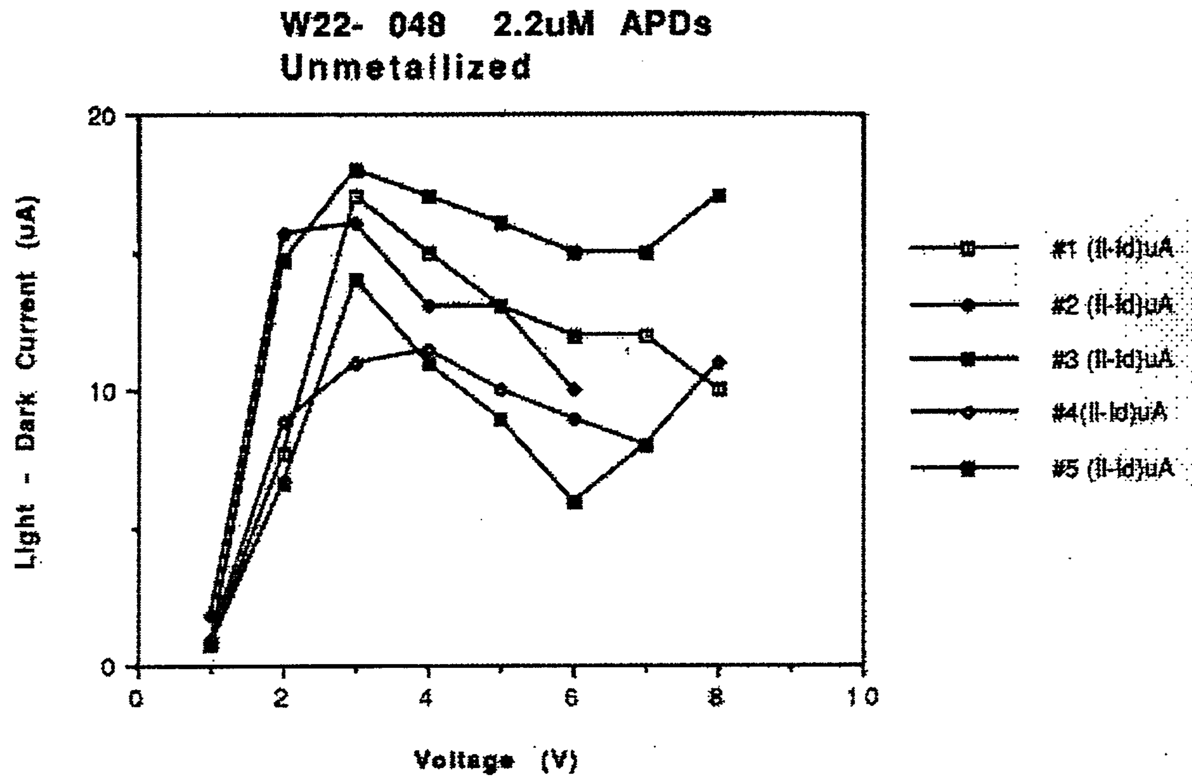
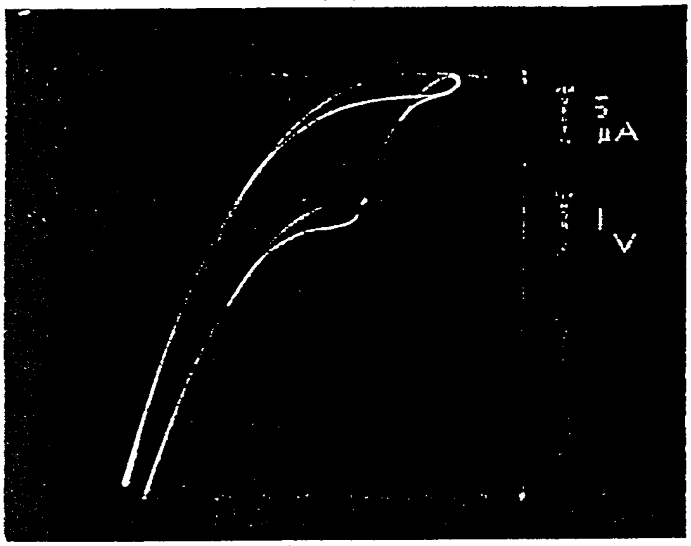


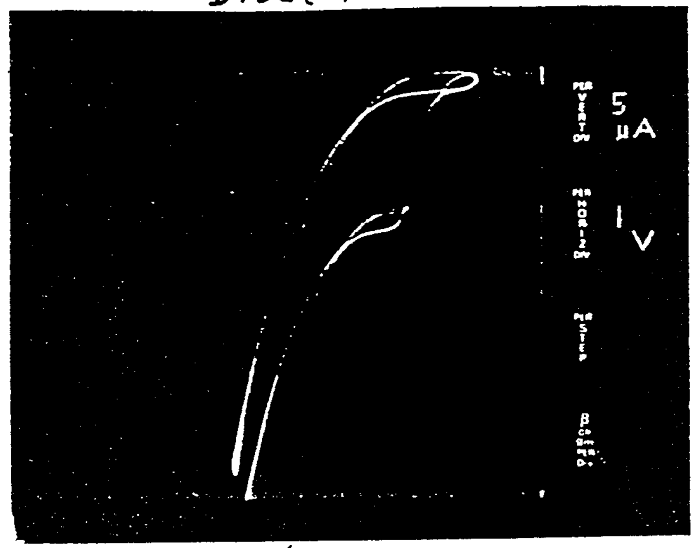
Figure 2: I-V characteristics of <u>unmetallized</u> APD's

Diode #1



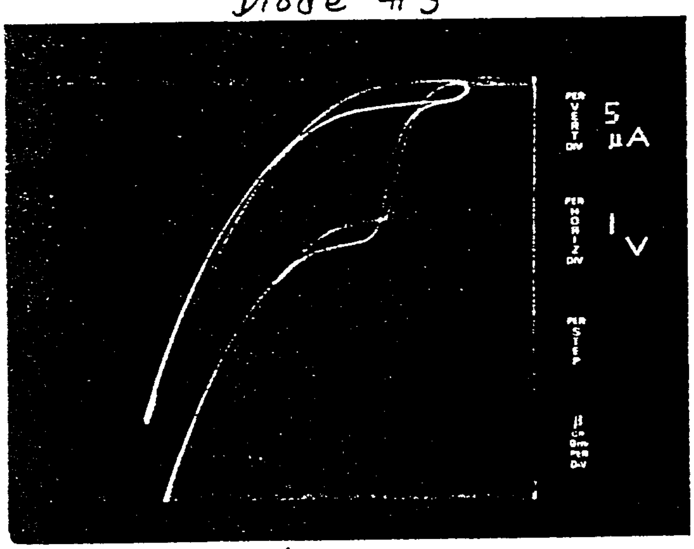
V_R

Diode #2



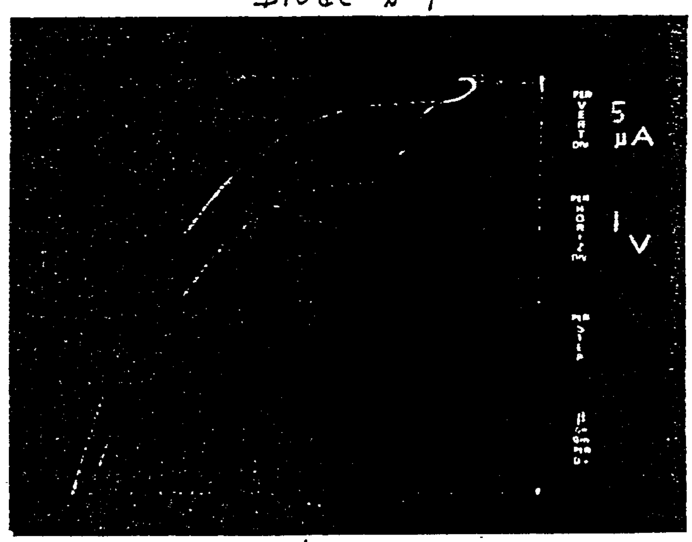
V_R

Diode #3



V_R

Diode #4



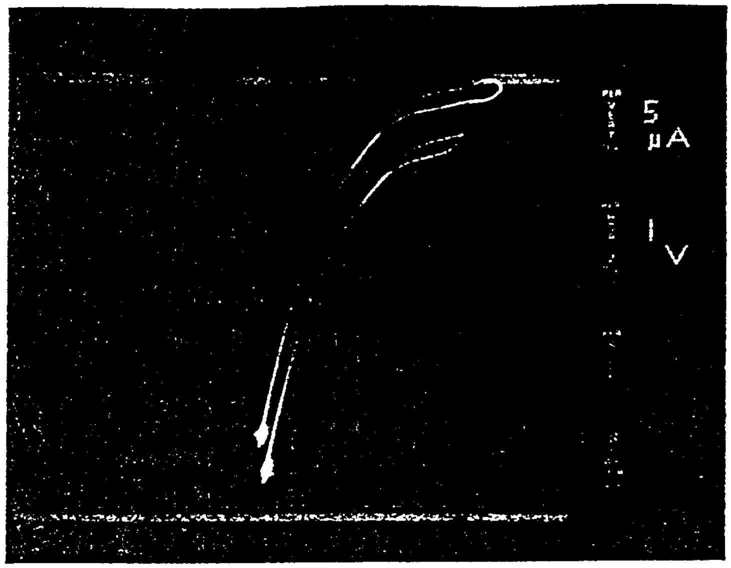
V_R

Figure 3: W22-048 2.2μm APDs Unmetallized Wafer V_r (with and without Illumination)

Table 2: W32-038 2.2 μm APDs

uA

V	Diode # 1		Diode # 2		Diode # 3		Diode # 4		Diode # 5		Comments
	Id	Il	Id	Il	Id	Il	Id	Il	Id	Il	
1	0.1	2.0	0.1	1.5	0.0	0.0	0.0	0.0	0.2	0.2	100μm Diameter "Snowman"
2	0.2	7.0	0.2	7.0	0.1	0.5	0.1	2.0	0.4	1.0	Meas. Pattern Wafer Unmetallized
3	0.3	12.0	0.4	11.0	0.5	10.0	0.2	15.0	0.5	2.5	
4	0.5	14.5	1.5	11.5	1.0	10.0	0.8	16.0	0.8	6.0	
5	1.8	15.0	3.0	12.5	1.5	10.5	3.0	17.0	1.2	9.5	
6	3.0	16.0	5.0	15.0	2.5	12.0	6.0	19.0	4.0	10.0	
7	5.0	18.0	9.0	18.0	4.0	15.5	10.0	23.0	8.0	11.0	
8					6.5	20.0	16.0	28.0	12.0	13.5	



Diode #5 VR

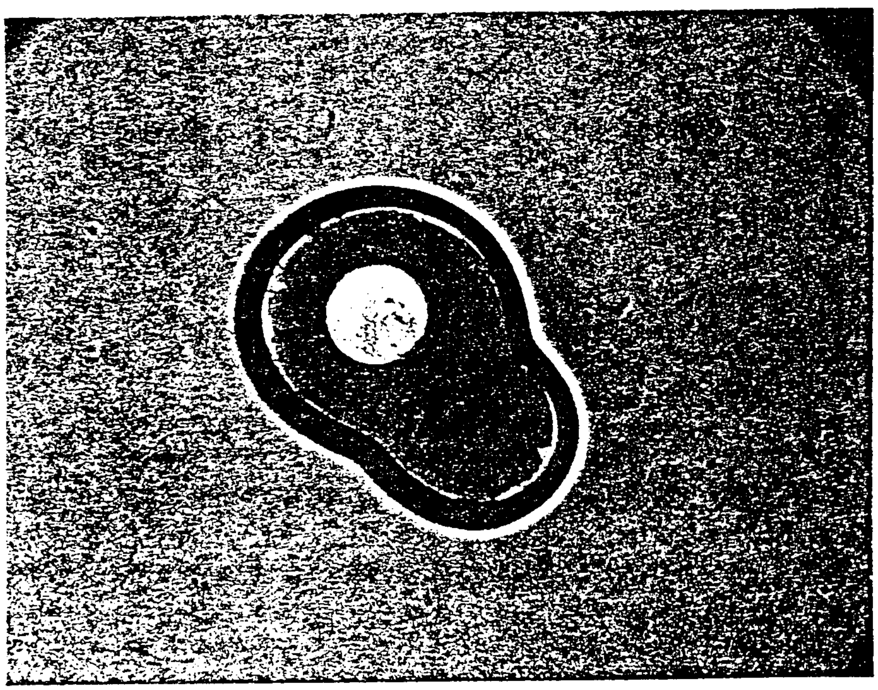


Figure 4: W32-038 2.2μm APDs Metallized Wafer I-V characteristics (with and without Illumination). Bottom photo is our "snowman" contact structure with 50 μm contact dot.

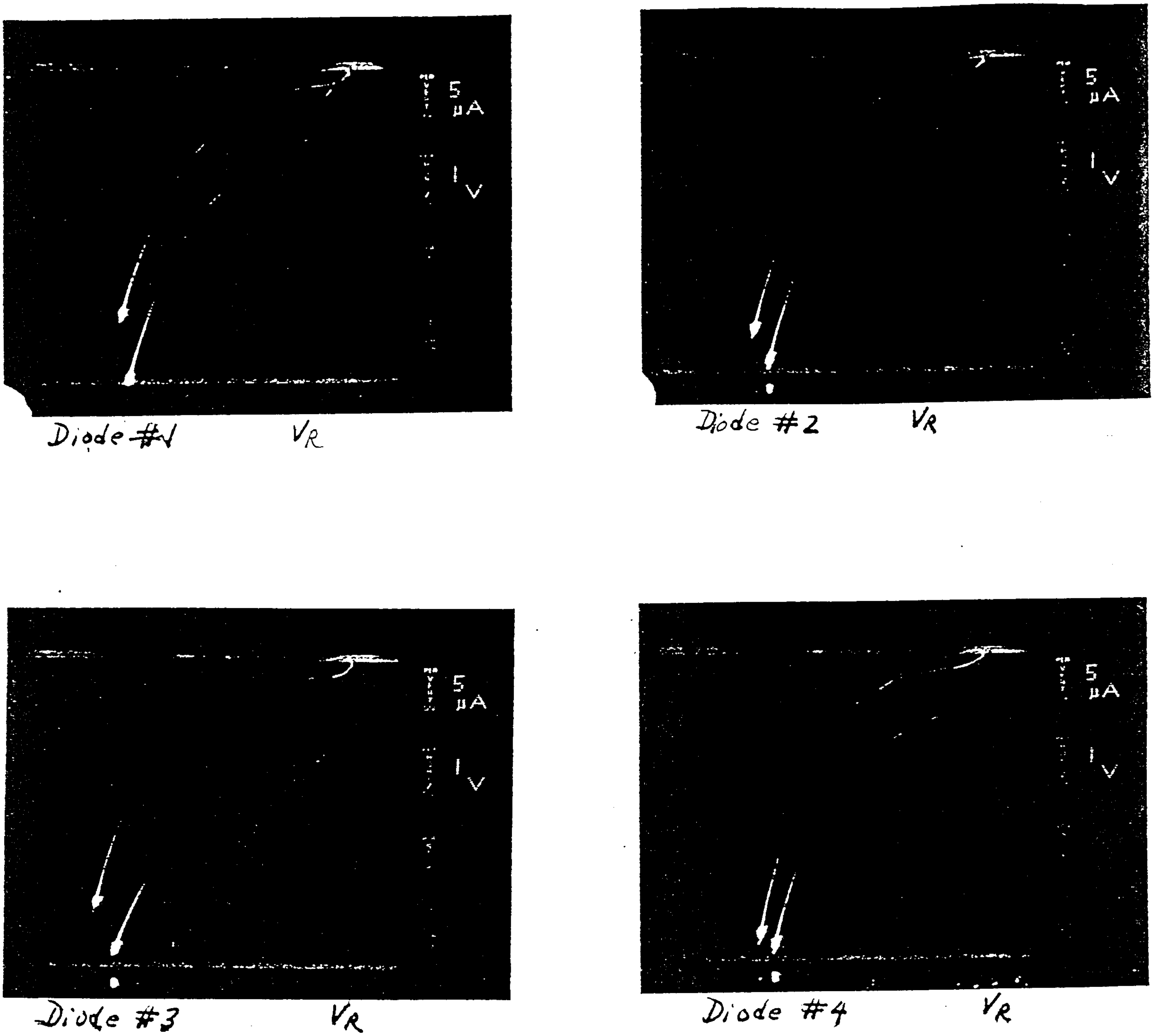
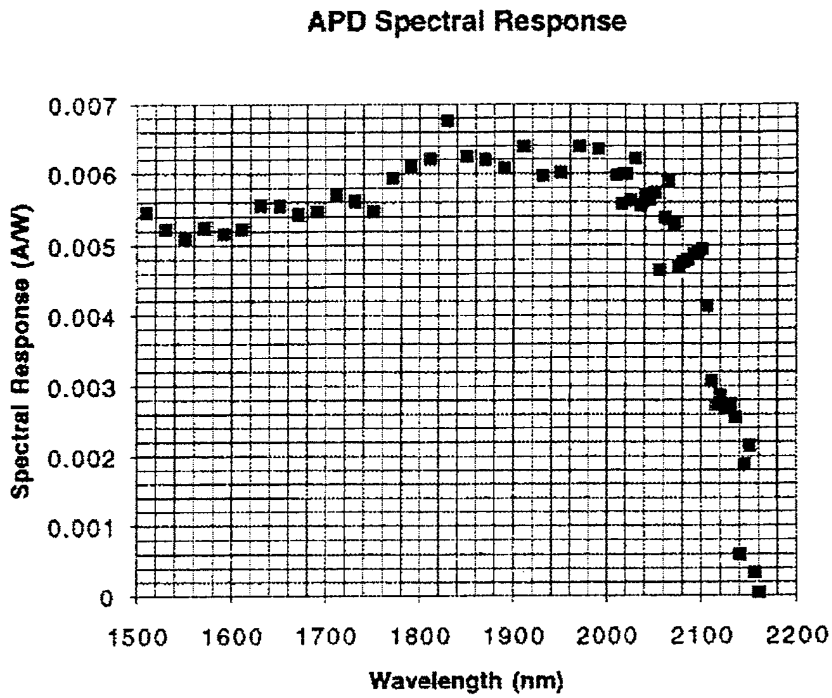


Figure 5: W32-038 2.2µm APDs Metallized Wafer I-V characteristics (with and without Illumination)

Table 3: W32-038 2.2 μm APDs

uA

V	Diode #1		Diode #2		Diode #3		Diode #4		Diode #5		Comments
	Id	Il	Id	Il	Id	Il	Id	Il	Id	Il	
1	1.0	5.0	1.0	5.0	1.0	13.0	1.0	2.5	1.0	5.0	100μm Diameter "Snowman" Mesa
2	2.0	12.5	2.0	12.0	1.5	18.0	2.0	10.0	2.0	7.5	pattern Wafer Metallized
3	3.5	14.0	3.0	13.5	2.0	19.0	3.0	12.5	5.0	11.0	
4	7.5	17.5	6.5	17.0	3.5	22.0	6.0	16.0	12.5	19.0	
5	11.0	22.5	11.0	22.0	6.0	24.5	11.0	21.5	26.0	32.5	
6	17.0	29.0	18.0	29.0	10.0	29.0	19.0	31.0	45.0	56.0	
7	27.0	40.0	27.5	42.0	36.0	36.0	33.0	44.0			
8	42.0	55.0	42.0	55.0	47.5	47.5	50.0	58.0			



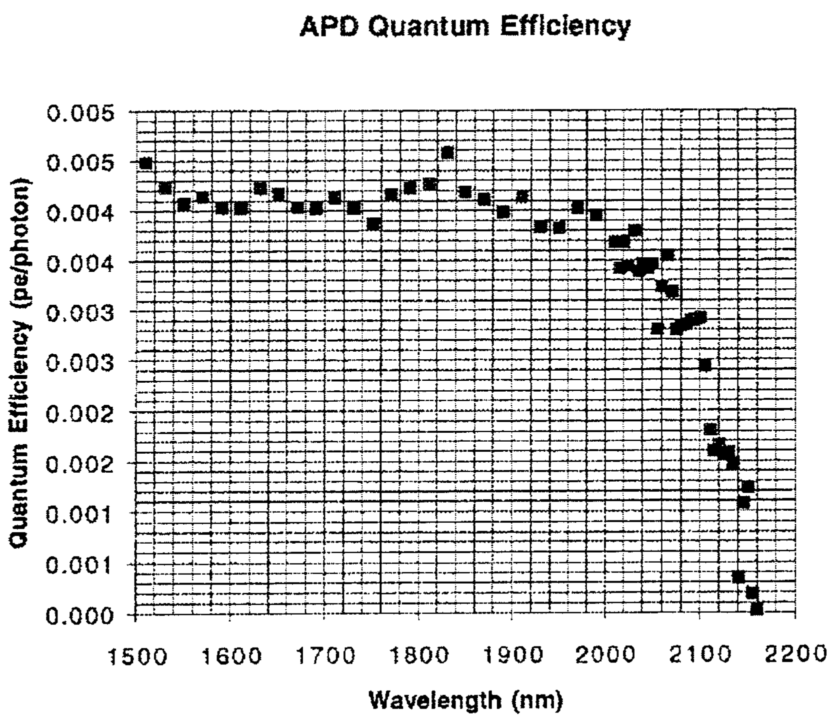


Figure 6: Responsitivity and quantum efficiency for the 2.1μm APD